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INVESTIGATION OF USING GLOBAL POSITIONING SYSTEM FOR AIR DATA SYSTEM CALIBRATION OF GENERAL AVIATION AIRCRAFT (HAVE PACER II)

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JANUARY 1996

FINAL REPORT

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AIR FORCE FLIGHT TEST CENTER
EDWARDS AIR FORCE BASE, CALIFORNIA
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This report presents the results of an evaluation of the suitability of using handheld Global Positioning System (GPS) receivers using course acquisition code to perform an air data system calibration. The two testbeds were an aerospatiale Tobago and a Rutan Long EZ, both general aviation single engine land aircraft. The test objective was to evaluate the suitability of commercial GPS receivers as measuring devices for general aviation air data system (ADS) calibration. Emphasis was on a handheld GPS and data collection devices. The goal was to develop a technique to accomplish an ADS calibration on a low-speed (under 200 knots calibrated airspeed) aircraft, using only commercial GPS equipment. After an all-altitude airspeed comparison technique was developed, a calibration of the ADS of an uninstrumented general aviation aircraft was completed. Overall, the commercial GPS receivers were suitable as measurement devices for ADS calibrations. Any current, commercially available receiver could be used without the need for differential GPS receivers or rigorous postprocessing of receiver data.

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PREFACE

This report contains the results of using handheld Global Positioning System (GPS) receivers using coarse acquisition (C/A) code to perform an air data system calibration. The investigation followed earlier work performed by the Test Pilot School (TPS) HAVE PACER project during an air data system (ADS) calibration of the F-16B using a differential GPS pod Previous flight testing at the University of Tennessee Space Institute concluded that GPS C/A code would not be adequate for ADS calibration because of the uncertainty in the vertical position. An Aerospatiale TB-10 Tobago and a Rutan Long EZ were used as flying testbeds. Both were general aviation single engine land aircraft. Testing was requested by the commandant of the USAF TPS as part of the Test Management Phase Curriculum. The test was conducted by a test team from the TPS class 95A under Job Order Number M94C1400.

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EXECUTIVE SUMMARY

This report contains the results of using handheld GPS receivers using C/A code to perform an ADS calibration. Testing was performed as part of the Test Management Phase of the TPS curriculum. Thirty-six sorties totaling 67.9 hours were flown from 15 September to 27 October 1995 at the Air Force Flight Test Center, Edwards Air Force Base, California. The test aircraft were a production representative Aerospatiale TB-10 Tobago and a Rutan Long EZ. The Tobago was modified with a precision airspeed indicator.

The test objective was to evaluate the suitability of commercial GPS receivers as measuring devices for general aviation ADS calibration. Emphasis was on handheld GPS and data collection devices. The goal was to develop a technique to accomplish an ADS calibration on a low-speed (under 200 knots calibrated airspeed) aircraft, using only commercial GPS equipment. After an all altitude airspeed comparison technique was developed, a calibration of the ADS of an uninstrumented general aviation aircraft was completed.

All test objectives were met. Flight test results revealed that the precision (P) and C/A coded receivers did not achieve the same level of accuracy as the flyby tower theodolite in the altitude comparison method. Even though relative GPS theory predicted that using either P or C/A code receivers should be as accurate as the flyby tower theodolite, user and receiver segment uncertainty was larger than expected.

The velocity position error corrections from both the P and C/A code receiver data were comparable to the data taken on the groundspeed course. Using the GPS receiver groundspeed data as the truth source, the ADS of the Tobago was calibrated at 5,000 and 10,000 feet pressure altitude using a new all altitude airspeed comparison method developed by the test team. That same all altitude airspeed comparison method was then used to complete a pitot-static system calibration on a Long EZ. The results were comparable to an earlier pitot-static system calibration performed by the Army on the same type of aircraft and ADS.

Overall, the commercial GPS receivers were suitable as measurement devices for ADS calibrations using the all altitude airspeed comparison method. Any current, commercially available receiver could be used without the need for differential GPS receivers or rigorous postprocessing of receiver data. However, in order to accomplish the altitude comparison method, the GPS C/A coded receiver data must be able to be postprocessed with differential or carrier phase corrections.

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INTRODUCTION

BACKGROUND

As part of the USAF commitment to dual-use technology, the commandant of the USAF Test Pilot School (TPS) directed an investigation of civil Global Positioning System (GPS) (coarse acquisition [C/A] code only, with selective availability active) for use as a truth source for general aviation aircraft air data system (ADS) calibrations. Use of commercially available GPS receivers would allow any general aviation or experimental aircraft operator to calibrate the aircraft ADS without the expensive outside support of surveyed courses or radar tracking. This report presents the results on the feasibility of performing an ADS calibration on an Aerospatiale TB-10 Tobago and Rutan Long EZ using commercial GPS receivers.

This investigation followed previous work performed by the TPS HAVE PACER project during an ADS calibration of the F-16B using a differential GPS pod (Reference 1). That test program determined that unaided GPS precision (P) code receivers were sufficient to calibrate the F-16B ADS within the accuracy of current truth sources, in this specific case, a ground based radar. Previous flight testing at the University of Tennessee Space Institute concluded that GPS C/A code would not be adequate for ADS calibration because of the uncertainty in the vertical position (Reference 2). Both GPS P and C/A code receivers were used to establish methods and a level of GPS accuracy needed to perform an ADS calibration on a general aviation aircraft.

This investigation consisted of three phases. In the initial phase, data from GPS receivers using both the P and C/A code were compared to data collected on the groundspeed course and tower flyby (TFB) course. Once a sufficient level of statistical accuracy was established using the two classic calibration methods as truth sources, the second phase began. The second phase investigated pressure field effects at 5,000 and 10,000 feet pressure altitude (PA). Also during the second phase, an all-altitude airspeed comparison flight test technique was developed to determine ADS calibrations using GPS as a truth source. The final phase checked the operational suitability of the new technique on a Long EZ to perform an ADS calibration of the aircraft.

Thirty-six sorties were required to complete this evaluation between 15 September and 27 October 1995. The 67.9 hour flight test program consisted of 12 hours of checkout and practice, 41.3 hours testing in the Tobago and 14.6 hours in the Long EZ. This evaluation was conducted by students of the TPS, Edwards AFB, California and funded under Air Force Flight Test Center Job Order Number M94C1400. All flights were flown from the Air Force Flight Test Center at Edwards AFB, California.

TEST ITEM DESCRIPTION

TB-10 Tobago:

The TB-10 Tobago, tail number N5543G, was a four-seat general aviation aircraft built by the Socata group of the Aerospatiale Company. The TB-10 Tobago was powered by a Lycoming O-360-A1AD, four-cylinder, air-cooled engine rated at 180 maximum horsepower. Figure A3 is a line drawing of the aircraft. A total temperature probe was installed underneath the right wing upstream of the landing gear to augment the digital outside air temperature sensor on the aircraft. The temperature probe consisted of a thermocouple taped to the aircraft. Aerodynamic effects were considered negligible. Pertinent resolutions and accuracies for the instrumentation used on the aircraft are shown in Table B1. The Tobago was considered production representative and met applicable Federal Aviation Regulations (FARs). Additional information on the Tobago was contained in the *Pilot's Information Manual* (Reference 3).

A schematic diagram of the Tobago ADS is shown in Figure A1. The ADS uses a pitot tube under the left wing 6 feet from the wingtip. The flush static pressure sources were located on either side of the fuselage 89 inches from the rear of the plane. A sensitive airspeed indicator was added as shown in Figure A1 by attaching additional static and pitot lines to the current system. The entire system underwent a pretest and post-test leak check. The leak checks were accomplished in accordance with FAR part 43, which required that the system leak no more than 100 feet at 1,000 feet of altitude, and no more than 5 knots of airspeed at the structural airspeed limit of the aircraft. Once the leak check passed FAR requirements, the Tobago pitot-static system was considered production representative. After completion of flight test, the additional sensitive airspeed indicator was removed and the attach points sealed. The aircraft then underwent another leak check to restore its original airworthiness.

Long EZ:

The Long EZ, tail number N271J, was an experimental, tandem-seat, swept-wing, forward-canard, pusher-propeller aircraft. The aircraft, pictured in Figure A4, was equipped with a Lycoming O-320-D3G horizontally opposed four-cylinder engine. The engine was rated at 160 horsepower at 2,700 rpm. The engine was modified from the stock configuration with an electronic ignition system and fuel injection. The aircraft had fixed main landing gear, with a retractable nose gear, and a landing brake which extended from underneath the aircraft. A total temperature probe was located beneath the nose of the aircraft. Pertinent resolutions and accuracies for the instrumentation used on the aircraft are in Table B2. Additional information on the Long EZ was contained in the Pilot's Operating Handbook (Reference 4).

The Long EZ ADS used an unheated pitot tube in the nose of the aircraft. A flush static port was located on the left fuselage under the canard. A calibrated altimeter and calibrated sensitive airspeed indicator were used for data instrumentation. Given that the Long EZ was a home-built aircraft, the term production representative does not apply. However, no modifications were made to the ADS during testing. A schematic of the Long EZ ADS is shown in Figure A2.

GPS Receivers:

The primary GPS receiver used during flight test was the Garmin GPS AVD 100 manufactured by Garmin International. This portable system could track up to eight satellites on one channel and used Garmin MultiTrac© software to calculate the navigation solution. Since the software was proprietary to Garmin, data reduction assumed that both ground-based and airborne receivers were navigating from the same satellites. This receiver could only pick up the C/A code from the GPS satellites, which was the primary reason for the large uncertainties in the position seen in Table B3. The Garmin GPS 100 had a 0.75- by 3-inch liquid crystal display (LCD) which displayed position, groundspeed along a track, estimated location error, as well as other navigation data. The Garmin 100 was powered externally or by rechargeable battery packs. Additional information on the Garmin 100 was contained in the Owner's Manual (Reference 5).

The other receiver used was a portable lightweight GPS receiver (PLGR+) made by the Collins Avionics and Communications Division of Rockwell Aerospace. The PLGR+ could receive the encrypted precision code (Y code) for improved geometric position accuracy. The utility of this receiver was that it simulated the accuracies predicted for the Wide Area Augmentation System (WAAS), scheduled to be operational by 2001 (Reference 6). The PLGR+ was a five-channel receiver that automatically picked the best four satellites to calculate a position solution. The PLGR+ received only the L1 frequency from the GPS satellites which increased the error from ionospheric effects as compared to a two-frequency receiver. The PLGR+ had a 1- by 3-inch LCD which displayed position, groundspeed along a track, estimated location error, as well as other navigation data. The PLGR+ was powered externally or by rechargeable battery packs. The published accuracy for the PLGR+ can be found in Table B3. Additional information on the PLGR+ was contained in the Operations Manual (Reference 7).

TEST OBJECTIVES

The general objective was to evaluate the suitability of commercial GPS receivers as measuring devices for small aircraft ADS calibration. Emphasis was on handheld GPS and other portable data collection devices. The goal was to develop a technique to accomplish an ADS calibration on a low-speed (under 200 KCAS) aircraft, using only commercial GPS equipment. Finally, using the new calibration technique, calibrate the air data system of another general aviation aircraft.

The specific objectives were to:

1. Compare air data system calibration results from the GPS (P and C/A codes) with the flyby tower.

2. Compare air data system calibration results from GPS (P and C/A codes) with the groundspeed course.

3. Develop and evaluate an all-altitude technique to calibrate the ADS at 5,000 and 10,000 feet to account for or eliminate wind effects.

4. Develop procedures to implement the GPS calibration flight test technique.

The success criteria determined for these specific objectives was to collect sufficient data to compare altitude and velocity position error corrections calculated from these various sources. The last specific objective required that enough qualitative data be collected to evaluate an all-altitude airspeed comparison method for an ADS calibration of a Long EZ.

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TEST AND EVALUATION

TEST PROCEDURES

The TB-10 Tobago was flown using two low altitude flight test techniques (FTTs) to collect and compare data for an ADS calibration using portable, commercial GPS receivers. In addition, an all-altitude airspeed comparison technique was developed to collect calibration data using the GPS receiver. During all testing, the TB-10 was flown in the cruise configuration with flaps retracted and pitot heat in the OFF position. In the final phase of the project, the all-altitude airspeed comparison method was used to calibrate the ADS of a Rutan Long EZ aircraft. The Long EZ was also flown in the cruise configuration with nosewheel and landing brake retracted.

The first phase of flight testing, using the TB-10, compared pitot-static system data from the tower flyby (TFB) FTT and the groundspeed course (GSC) FTT to GPS altitude and groundspeed data. The aircraft was flown past the flyby tower at approximately 10-knot increments over the range from 70 KIAS to the maximum velocity airspeed in level flight. Data tolerance required the aircraft not exceed rates of climb or descent of ±50 feet per minute and at least one wingspan (32 feet) above the ground to avoid in-ground effect. Theodolite data were used along with pressure altitude and temperature readings in the tower and in the aircraft to calculate static pressure source position error corrections. All data were collected in calm air.

During the flyby tower passes, altitude data from GPS receivers in the aircraft and the tower were collected (the procedures are summarized in Table E1). A pair of commercially available Garmin GPS AVD 100s were used to collect data using the C/A code from the GPS satellites. Another pair of PLGR+ provided data using the P code to simulate the level of accuracy expected when the Federal Aviation Administration's WAAS becomes operational around 2001. The two different types of GPS receivers were used to evaluate two levels of accuracy for comparison of the two classic FTTs mentioned above. The GPS receivers were used in accordance with relative GPS theory which states that two receivers in different locations, using the same satellites, would provide an accurate measurement of the distance between them (Reference 8). The difference in altitude measurements from the GPS receivers in the aircraft and the tower provided the same function as the theodolite in the flyby tower.

A typical error budget for a position solution from a GPS receiver include satellite, user, and propagation errors. With two receivers, theoretically, the satellite and propagation error sources could be eliminated. Assuming both receivers were in the same general location as they were in this investigation, the atmospheric effects from the ionosphere and troposphere could be assumed identical. When a difference in position was taken between the two receivers, the atmospheric effects dropped out. In the same way, the effects of selective availability (i.e., frequency, time, and ephemeris dithering) could also be eliminated. The only error sources remaining were those affecting the user or individual receivers (e.g., multipath, masking angle, and internal clock errors). In order for the GPS receiver data to be within the same level of accuracy as the flyby tower theodolite, the error in relative altitude between the aircraft and the ground must be less than ±5 feet.

For slower velocity aircraft, the GSC provided more accurate data for the calculation of velocity static position error correction compared to the flyby tower. This project used that advantage by flying the TB-10 over the 4-statute-mile course at approximately 10-knot increments over the range from 70 KIAS to the maximum velocity airspeed in level flight (Table E2). By flying both up and down the course in calm air, the effects of wind were minimized. Distance-over-time measurements on the course were then used to calculate an average ground velocity. The ground velocity was then assumed to be the aircraft true velocity through the airmass. The true velocity could then be used with indicated altitude, velocity, and temperature measurements to determine the static pressure source position error.

The two types of GPS receivers were also used during the GSC runs. The receivers provided a groundspeed from the Doppler shift of the GPS signal (Reference 9). The GPS groundspeed measurements had less uncertainty than the GPS altitude data. The GPS ground velocity was also assumed to be the true velocity and was used in the calculation of the static position error. Data tolerances over a 1-mile section of the course were: higher than one wingspan above the ground, ±1 knot of the indicated target airspeed and reported control tower steady winds less than 10 knots.

The second phase of testing provided a method to collect data for an ADS calibration without the need for external facilities like a flyby tower or a surveyed groundspeed course. The all-altitude airspeed comparison method was flown at 5,000 and 10,000 feet PA assuming that the GPS groundspeed could be used as the truth source. The critical piece of data needed during this method was true velocity with wind effects reduced as much as possible. The only pertinent data available from the GPS receivers were groundspeed and groundtrack. The difference between the heading flown and the track gave an indication of wind direction and crosswind magnitude. The difference between the GPS groundspeed and an estimated true velocity gave an indication of head or tailwind magnitude. This technique required determining the direction of the winds aloft and then flying perpendicular to the winds.

A straight-forward approach was used to determine the winds aloft using the GPS groundspeed and groundtrack data. The forecasted winds aloft at 5,000 or 10,000 feet were first corrected to magnetic heading and were assumed to be correct. A true airspeed was estimated based on the outside air temperature and indicated airspeed. Then the Tobago was flown in a slow turn starting parallel to the forecasted direction of the wind at the specified altitude and airspeed. The turn was continued until the GPS groundspeed was equal to the estimated true airspeed. The aircraft was then stabilized on heading, groundspeed was noted, and then the reciprocal heading was flown. The GPS groundtrack and groundspeed were compared for the two directions. If the aircraft was flown perpendicular to the wind, the groundspeeds would be equal and the absolute difference between the groundtracks and headings flown would be equal. If that data were different, the actual direction of the wind could be determined from the data and the heading refined. To prevent infinite iterations, a difference of 5 knots in groundspeed between the two directions was determined to be acceptable.

The all-altitude airspeed comparison technique could also be thought of as a variation on the groundspeed course method. The groundspeed course requires flying back and forth along the course to find groundspeed. That groundspeed was assumed to be true airspeed and then the two passes averaged. At altitude, flying perpendicular to the wind minimized the head and tailwind components, allowing the assumption that groundspeed corrected for the drift angle was equivalent to true airspeed. The final true airspeed was determined by flying the direction normal to the wind for a 1-minute period and along the reciprocal heading. Groundspeeds corrected for the drift angle were then averaged. A run card for this FTT can be found in Table E3. For this method, data tolerances were within 100 feet of the target altitude, within ±1 knot indicated of the target airspeed and within 2 degrees of the desired heading during a test point. If the GPS groundspeed varied more than 5 knots during a run or the track varied more than 5 degrees the data were discarded. A 5-knot difference resulted in a 3-knot velocity position error correction according the sensitivity analysis summarized in Table D5.

The final phase of flight testing was performed on a Rutan Long EZ. An ADS calibration was conducted at 4,000 and 10,000 feet PA using the all-altitude airspeed comparison method described in the previous paragraphs. The 4,000-foot altitude was chosen for direct comparison with US Army data (Reference 10). The aircraft was also flown over a velocity range from 80 KIAS to the maximum velocity airspeed in level flight. Data tolerances were: within 100 feet of the target altitude, within ±1 knot indicated airspeed of the target, and within 1 degree of the desired heading during a test point.

Several types of data were required to measure the test performance toward the specific objectives. Plots of altitude static pressure source position error correction (ΔH_{pc}) and velocity static pressure source position error correction (ΔV_{pc}) versus instrument corrected velocity (V_{ic}) were used to compare data from the flyby tower, groundspeed course and GPS receivers. The data were taken over airspeeds ranging from 70 knots indicated (80 knots for the Long EZ) to the maximum velocity airspeed in level flight at approximately 10-knot increments. The same plots were used to examine pressure field effects for data taken at 5,000 and 10,000 feet PA using an all-altitude airspeed comparison technique.

Data reduction was accomplished by implementing the pitot-static equations found in the *Flight Test Engineering Handbook* (Reference 11) in several Microsoft Excel® spreadsheets. The primary goal for data reduction was for it to be simple and portable.

RESULTS AND ANALYSIS

All objectives were met. Sufficient data were collected to determine the accuracy of using GPS receivers to perform ADS calibrations. While the altitude static position error correction determined with the C/A code did not meet the 90 percent confidence criteria of ±75 feet, the correction determined with the P code did meet the required confidence interval. The ΔV_{pc} determined from both the C/A and P codes were adequate to meet the ±3-knot 90 percent confidence criteria. The all-altitude airspeed comparison method described in the test procedures was adequate to determine any pressure field effects which might be present at 5,000 and 10,000 feet PA. The all-altitude airspeed comparison method was used again to calibrate the ADS of a Long EZ at 4,000 and 10,000 feet PA.

Both C/A and P coded GPS receiver data were used to determine a height above the flyby tower during the altitude comparison method. The altitude position error corrections determined from both GPS and flyby tower theodolite are presented in Figure C1. The companion plot of ΔV_{pc} is found in Figure C2. The published altitude position error correction uncertainty for the TFB FTT was ±26 feet which corresponded to the approximate scatter of the data shown in Figure C1 (Reference 12). The scatter from the PLGR+ was within the same band, but the results from the Garmin GPS 100 data were much more scattered. That leads to the same conclusion as the University of Tennessee who determined the commercially available C/A code receiver was not as accurate as the flyby tower theodolite (Reference 2). One possible explanation was the inability of both the receivers, one in the aircraft and the other in the tower, to use the same satellites in the same way. The relative GPS theory used in this project assumed that both receivers used the same satellites to calculate a navigation solution (Reference 7). An accurate difference in altitude cannot be attained otherwise. From the results presented in the figures, the user segment and receiver errors were well above that of the flyby tower theodolite. The GPS altitude data did not have sufficient accuracy to replace the TFB FTT in providing altitude static pressure source position error corrections.

As stated before, the uncertainty in the GPS relative altitude data must be around ±5 feet to be comparable to the flyby tower theodolite data. A closer examination of the receiver and/or user segment error revealed that the relative error in altitude was greater than ±5 feet. The receiver pairs were placed 10, 20, and 30 feet apart with one of the receivers on a surveyed spot. The GPS location and altitude data were collected for 1 minute. With no difference in altitude between the two receivers, the altitude error for the PLGR+ ranged from 20 to 50 feet. The altitude error from the Garmin GPS 100 receivers was even larger. Commercially available C/A code GPS receivers were not adequate for use in an altitude comparison method. However, the uncertainties found in determining which satellites were tracked and how the navigation solution was calculated warrant further investigation. **A comparison between the flyby tower and GPS with commercial receivers that are capable of postprocessing differential and carrier phase data should be accomplished. (R2)**[1] Close attention must be paid to GPS antenna location and processing software during a subsequent investigation.

The groundspeed course provided the most promising results. During the early morning flights in calm winds, the aircraft predicted true velocity was comparable to the GPS groundspeeds. As expected from the published accuracies, the groundspeeds from the Garmin GPS 100 and the PLGR+ were always within 1 knot. Therefore, only the commercially available Garmin GPS 100 data were used for comparison to the GSC data.

The results from the GSC runs are shown in Figure C3 and C4. The TB-10 was flown over the course to collect 6 to 8 points per airspeed from 70 to 120 knots indicated airspeed. The GPS groundspeed data were comparable to the distance-over-time data for both velocity and altitude position error corrections. The GSC produced much less scatter than the TFB particularly when the GPS data

[1]The numerals preceded by an "R" within parentheses at the end of a paragraph correspond to the recommendation numbers tabulated in the Conclusions and Recommendations section of this report.

were compared. Looking at the ΔV_{pc} presented in Figure C4, both data sources produced similar results. The scatter was all within ±3 knots which achieved the 90 percent confidence level without further analysis. **The GPS groundspeed data should be used as a velocity truth source. (R1)**

The results from the all-altitude airspeed comparison method at 5,000 and 10,000 feet PA are presented in Figure C5 and C6. Prior to the start of this second phase of testing, the GPS groundspeed data were determined to be the measurement truth source. In both plots of ΔH_{pc} and ΔV_{pc}, no breakout in static pressure source position error can be seen for the altitudes flown. The lack of a breakout indicated that no pressure field effects existed around the side fuselage static ports at the two altitudes. A root sum squared analysis was performed to estimate the uncertainty of this method. Using sensitivities from the data analysis, the various measurements shown in Table D5 produced the depicted errors in the position error corrections. The final uncertainty was calculated at ±3.81 knots and ±29.2 feet.

The third and final phase of the investigation was used to perform an ADS calibration on a Rutan Long EZ. Using the all-altitude airspeed comparison method and the commercially available Garmin C/A coded receiver, the ADS was calibrated at 4,000 and 10,000 feet PA over the normal cruising range of the aircraft. The velocity correction results shown in Figure C7 were compared to a limited ADS calibration performed by the Army on another Long EZ with a similar pitot-static system configuration (Reference 12). The data follow the same trend showing that the Long EZ requires notable corrections at the slow end of the speed envelope. Figures C8 and C9 compare data from 4,000 and 10,000 feet PA for both the ΔH_{pc} and ΔV_{pc}. The ΔH_{pc} and ΔV_{pc} curves did not show much data scatter over the speed range. The subsequent lack of a breakout between the two altitudes indicated a lack of significant pressure field effects.

CONCLUSIONS AND RECOMMENDATIONS

Commercial Global Positioning System (GPS) receiver data were compared to data from classical flight test techniques used for air data system (ADS) calibrations. Coarse acquisition coded, commercial GPS receiver data were satisfactory for the purpose of ADS calibrations. The Garmin and portable lightweight GPS receivers (PLGR+) provided groundspeed data while flying over the Air Force Flight Test Center groundspeed course. Even though selective availability was active, the Garmin and PLGR+ groundspeed values were always within receiver display resolution and were comparable to the groundspeed calculated from the distance-over-time data. The groundspeeds obtained from the Doppler shift of the GPS signals were accurate enough to provide static pressure source position error correction curves without the use of a groundspeed course or other support aircraft as long as wind effects were minimized.

1. The GPS groundspeed data should be used as a velocity truth source. (Page 8)

Since GPS altitude measurements were notoriously inaccurate with selective availability active, C/A coded receiver data were not suitable for use in the altitude comparison method. Therefore, the commercially available receivers used during testing were not suitable for determining the altitude static pressure source position error correction for the Tobago ADS using the altitude comparison method. The altitude static pressure source position errors calculated from the PLGR+ P coded were comparable that calculated from the theodolite. Neither type of receiver was equipped to receive differential corrections or process carrier phase data, but some new commercially available GPS receivers have that capability. With an increase in altitude measurement accuracy from GPS receivers, the altitude comparison method may be shown not to require a theodolite-equipped tower.

2. A comparison between the flyby tower and GPS with commercial receivers that are capable of postprocessing differential and carrier phase data should be accomplished. (Page 7)

The all-altitude airspeed comparison method, partially based on the groundspeed course method, was developed to investigate pressure field effects on the Tobago and Long EZ. Based upon the results of the first phase, the GPS groundspeed data were used as the truth source. The all-altitude airspeed comparison method developed was adequate for minimizing wind effects at altitude. Data at 5,000 and 10,000 feet pressure altitude (PA) revealed negligible pressure field effects from the static position error correction curves for the Tobago. The same method was used on the Long EZ to evaluate the portability and ease of use for a general aviation pilot. Pressure field effects over the altitudes flown in the Long EZ were not significant. Comparison of the all-altitude airspeed comparison method with the Army flight test data at 4,000 feet PA showed the velocity position error correction followed the same trend and was within the same data scatter. The all-altitude airspeed comparison method developed for and used in this project was adequate for calibrating the ADS of general aviation aircraft.

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APPENDIX A

AIRCRAFT DIAGRAMS

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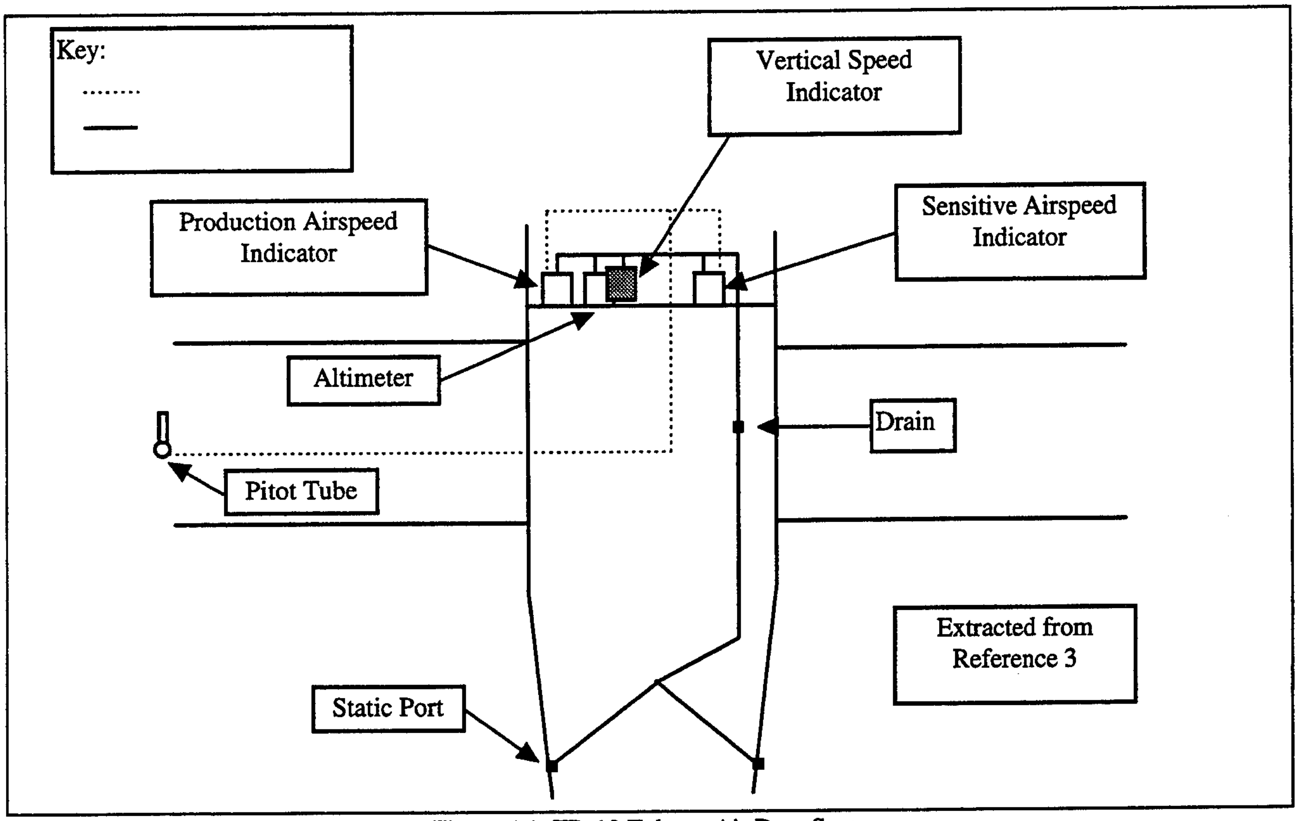

Figure A1 TB-10 Tobago Air Data System

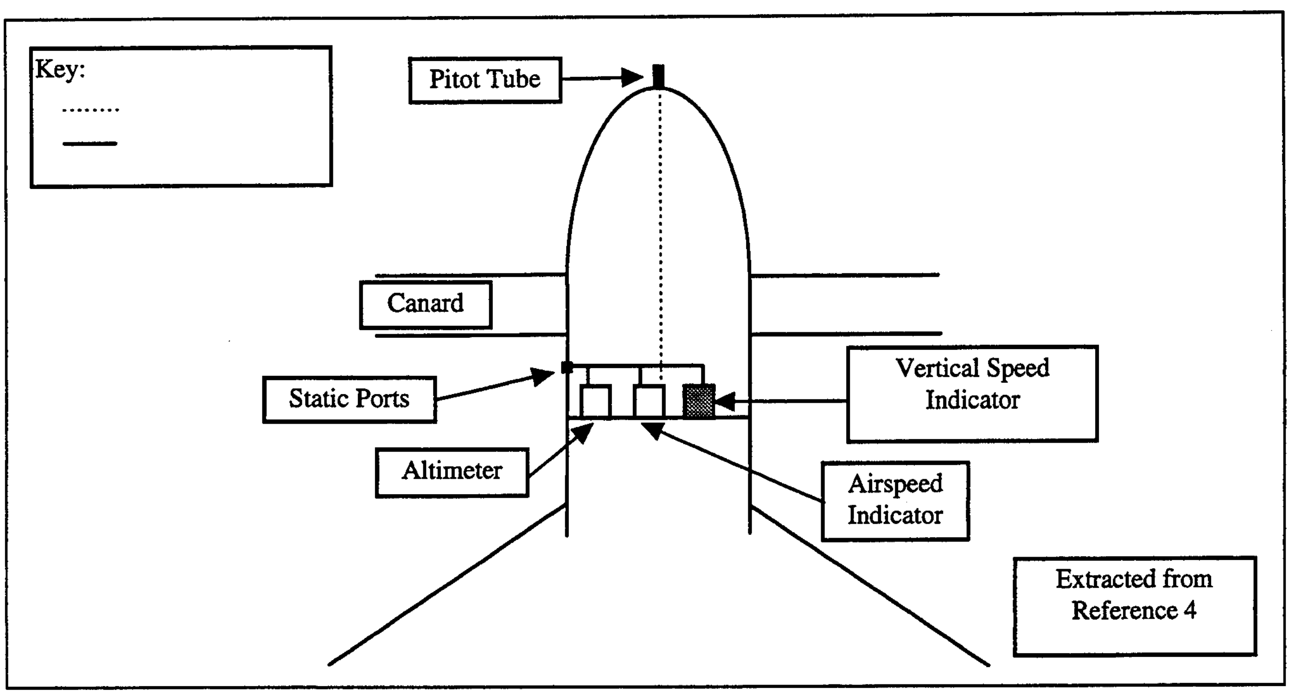

Figure A2 Long EZ Air Data System

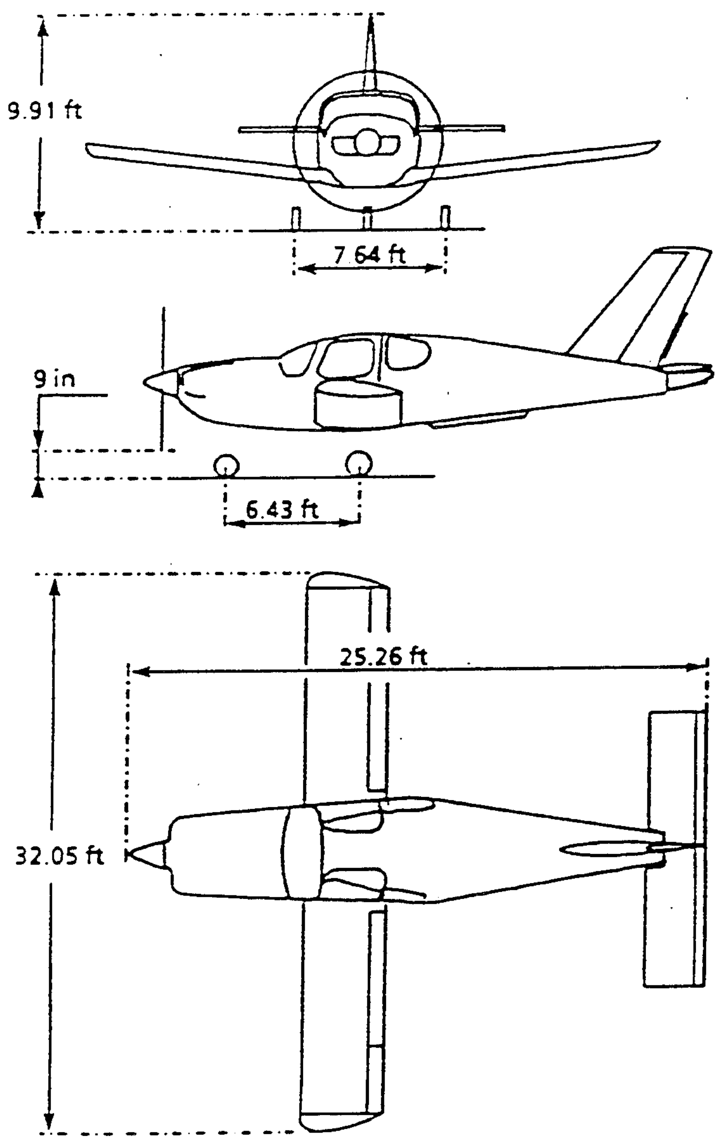

Figure A3 TB-10 Tobago Aircraft Depiction

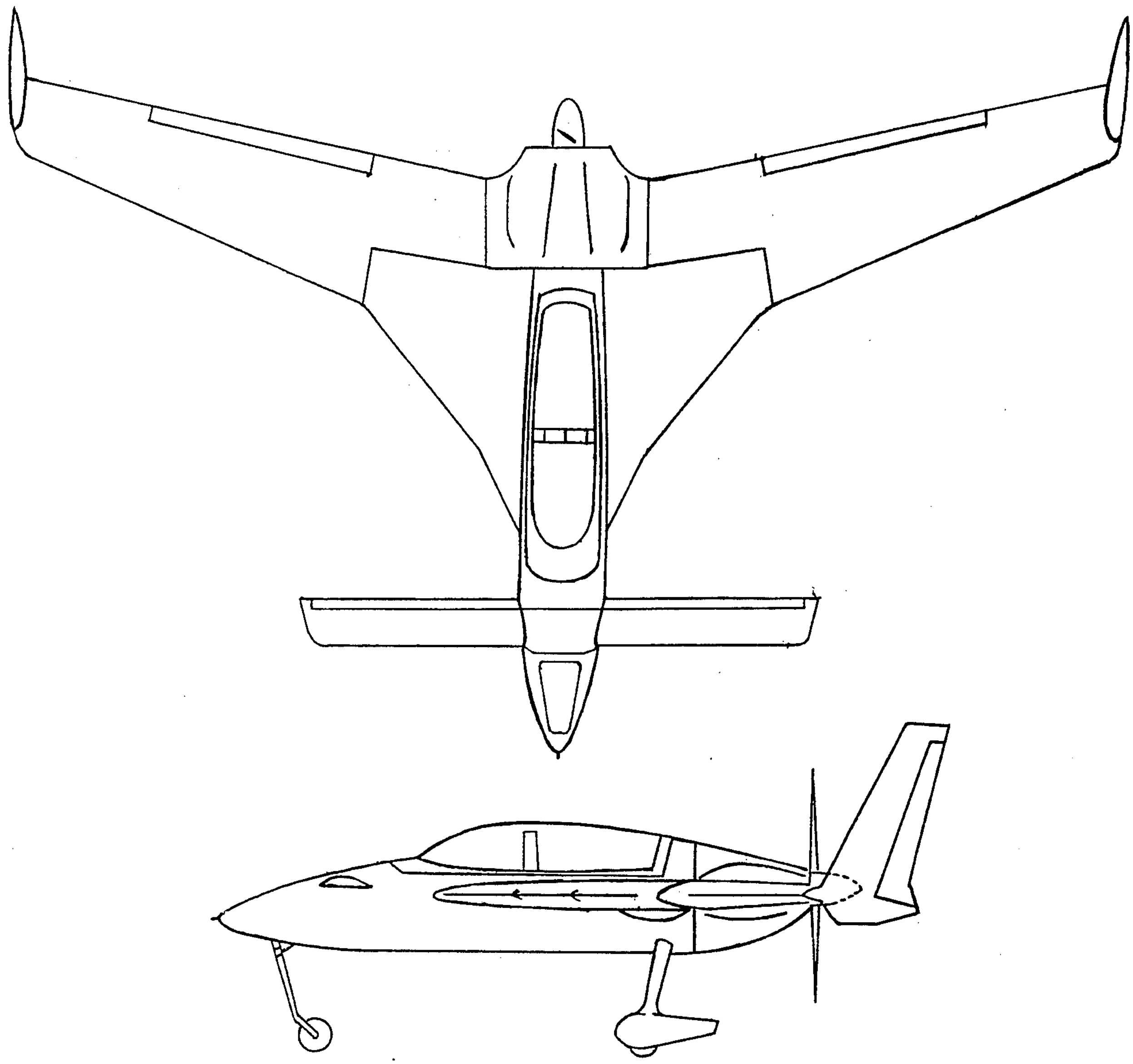

Figure A4 Long EZ Aircraft Depiction

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APPENDIX B

INSTRUMENTATION CHARACTERISTICS

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Table B1
PUBLISHED TOBAGO INSTRUMENTATION ACCURACIES

Instrument	Range	Resolution	Error or Uncertainty
Sensitive Airspeed Indicator (knots)	40 to 200	0.5	-0.5 to -1.5
Altimeter (feet)	0 to 20,000	10	+ 10 to 70
Installed Temperature Probe/Gauge (deg F)	-328 to 752	0.1	±(0.1 percent rdg + 1.0)
Barometer (inches of Mercury)	17.7 to 32.5	0.001	±0.009 over the range 23.6 to 31.3

Table B2
PUBLISHED LONG EZ INSTRUMENTATION ACCURACIES

Instrument	Range	Resolution	Error or Uncertainty
Sensitive Airspeed Indicator (knots)	40 to 200	0.5	-0.5 to 2.0
Altimeter (feet)	0 to 20,000	5	+10 to 70
Installed Temperature Probe/Gauge (deg F)	-328 to 752	0.1	±(0.1 percent rdg + 1.0)

Table B3
GPS RECEIVER ESTIMATED ERROR

GPS Receiver	Estimated Vertical Error[1]	Estimated Velocity Error[1]
Garmin 100 C/A code	493.4 feet	1.0+ fps
PLGR+ C/A code	493.4 feet	1.0+ fps
PLGR+ P code	95.4 feet	1.0 fps

Notes: 1. GPS - Global Positioning System
2. C/A - coarse acquisition
3. PLGR+ - portable lightweight GPS receiver
4. P - precision
5. fps - feet per second

[1] Note that these errors are the published accuracies of GPS using C/A code with Selective Availability active. Test data reduction used corrections to improve accuracy.

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APPENDIX C

AIR DATA SYSTEM CALIBRATION RESULTS

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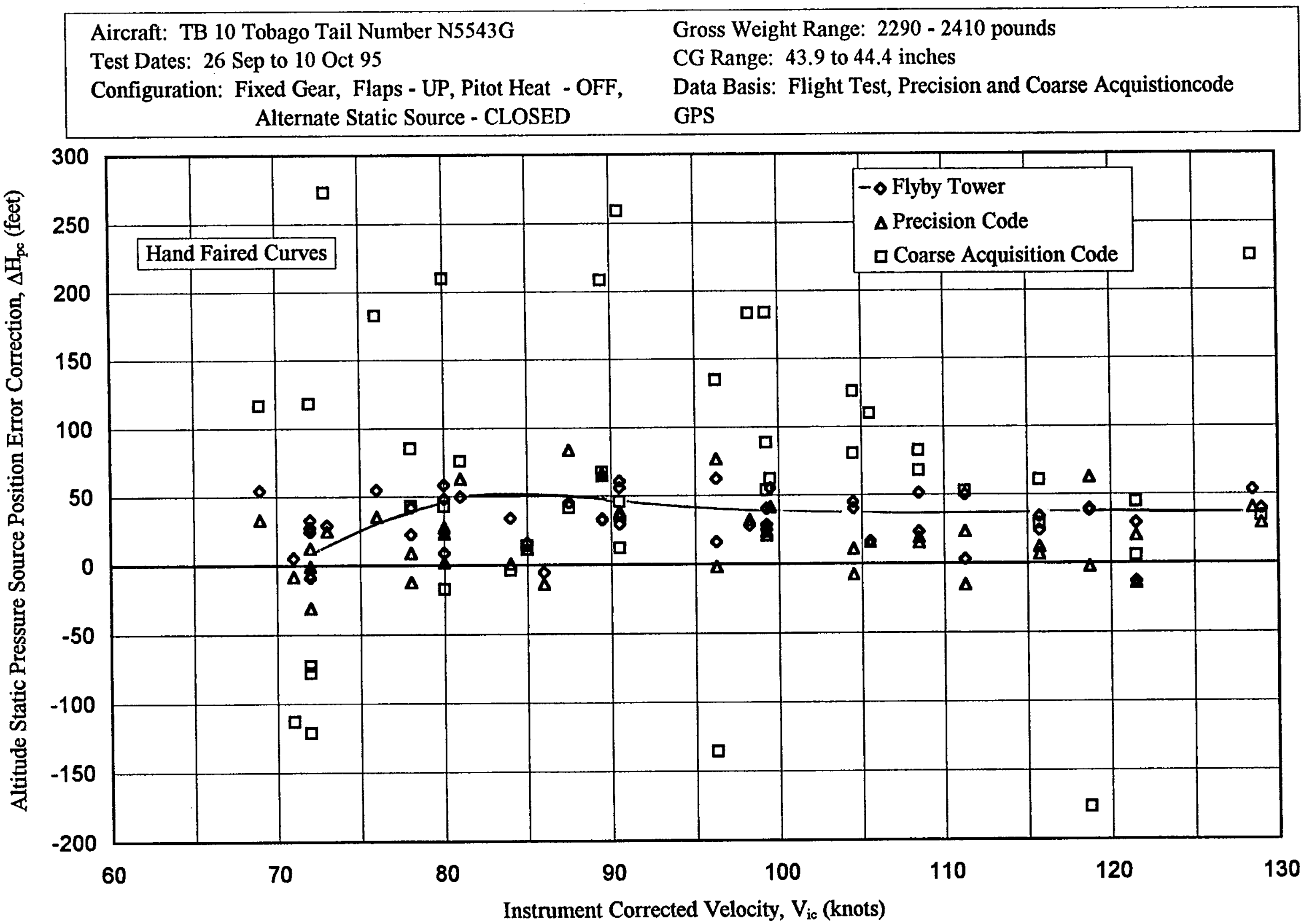

Figure C1 Tobago Altitude Static Pressure Source Position Error Correction Comparison of Flyby Tower and GPS Data

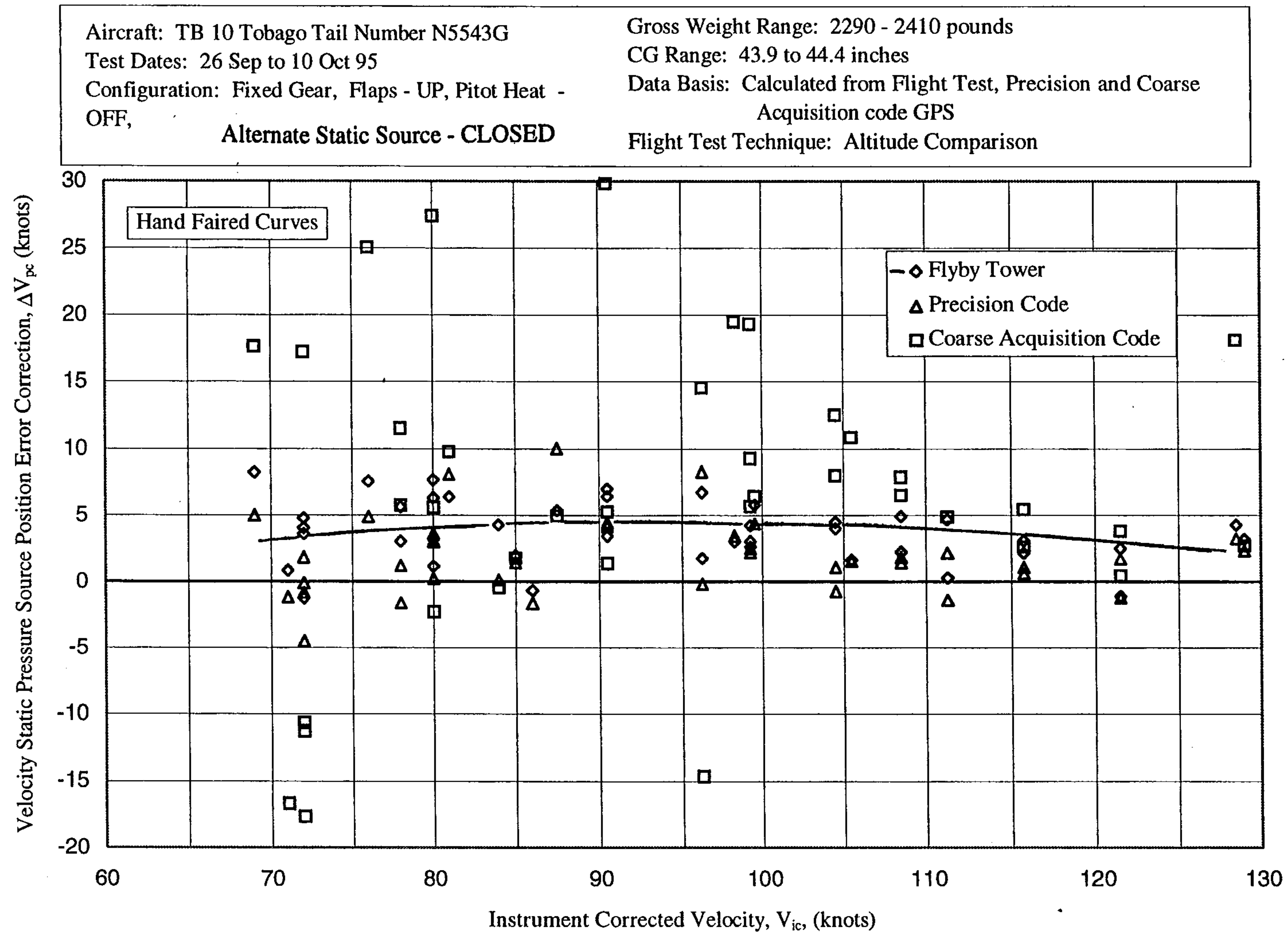

Figure C2 Tobago Velocity Static Pressure Source Position Error Correction Comparison of Flyby Tower and GPS Data

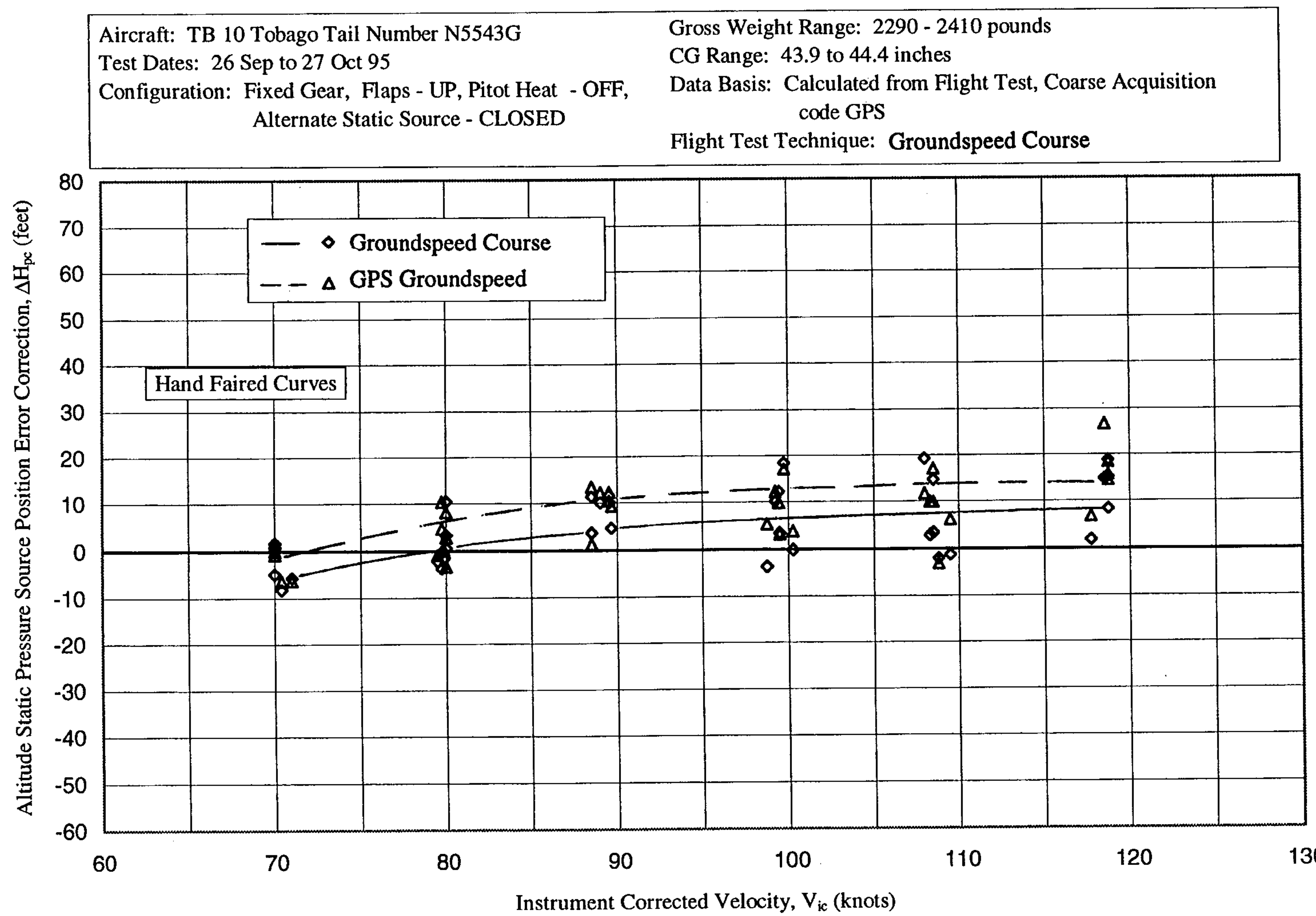

Figure C3 Tobago Altitude Static Pressure Source Position Error Correction Comparison of Groundspeed Course and GPS Data

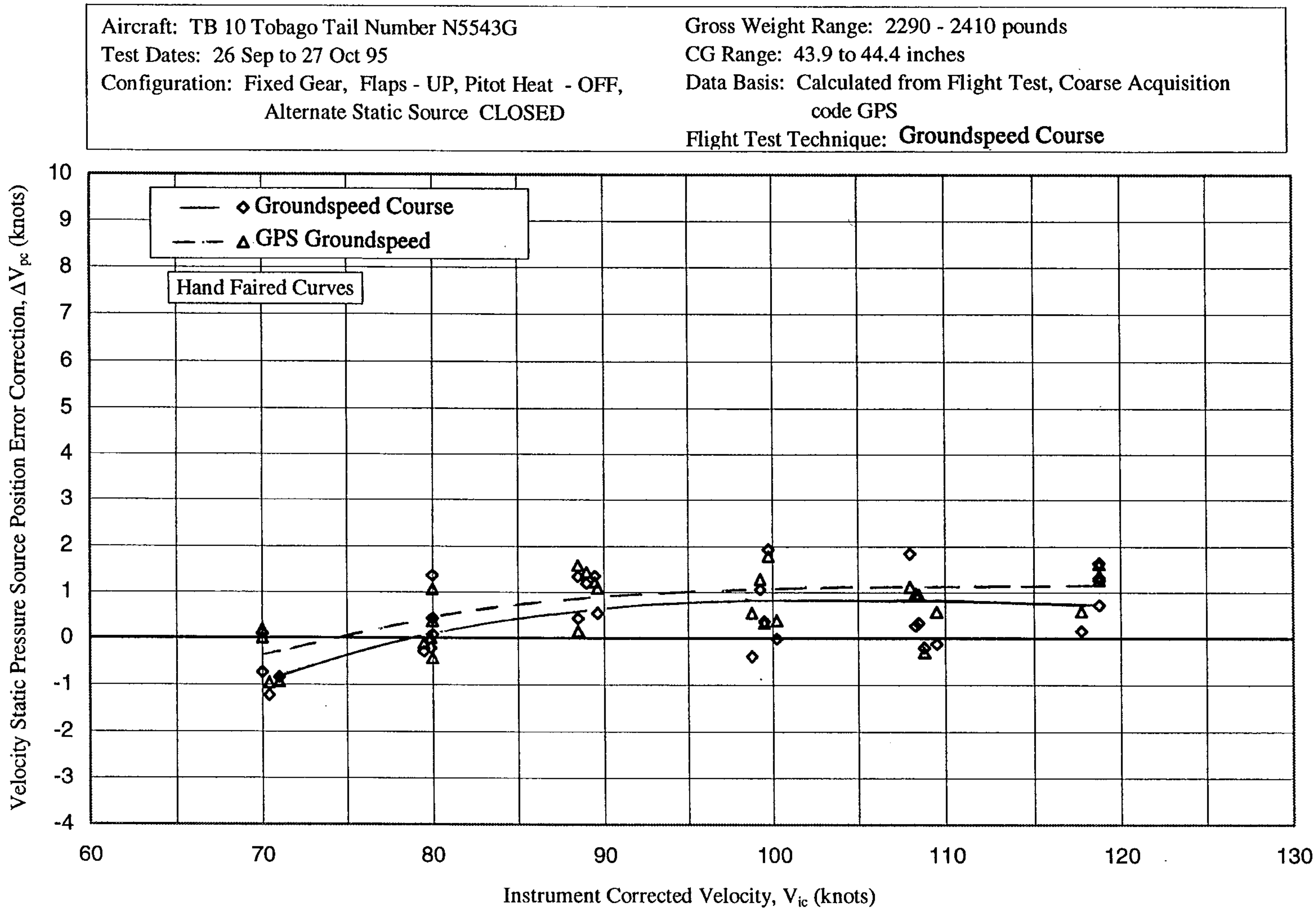

Figure C4 Tobago Velocity Static Pressure Source Position Error Correction Comparison of Groundspeed Course and GPS Data

Aircraft: TB 10 Tobago Tail Number N5543G
Test Dates: 26 Sep to 27 Oct 95
Configuration: Fixed Gear, Flaps - UP, Pitot Heat - OFF, **Alternate Static Source CLOSED**

Gross Weight Range: 2290 - 2410 pounds
CG Range: 43.9 to 44.4 inches
Data Basis: Calculated from Flight Test, Coarse Acquisition coded GPS
Flight Test Technique: All-Altitude Velocity Comparison Method

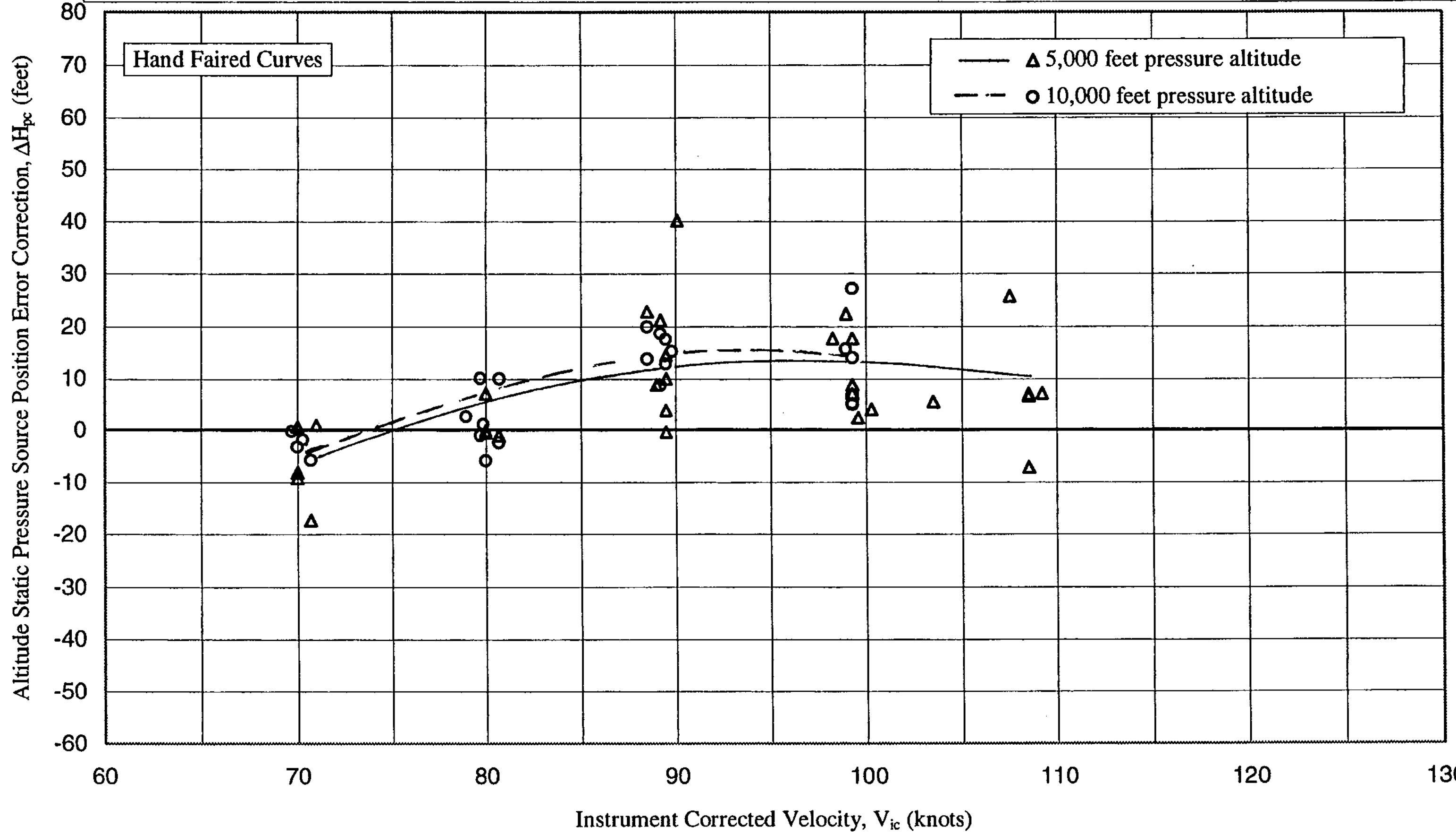

Figure C5 Tobago Altitude Static Pressure Source Position Error Correction

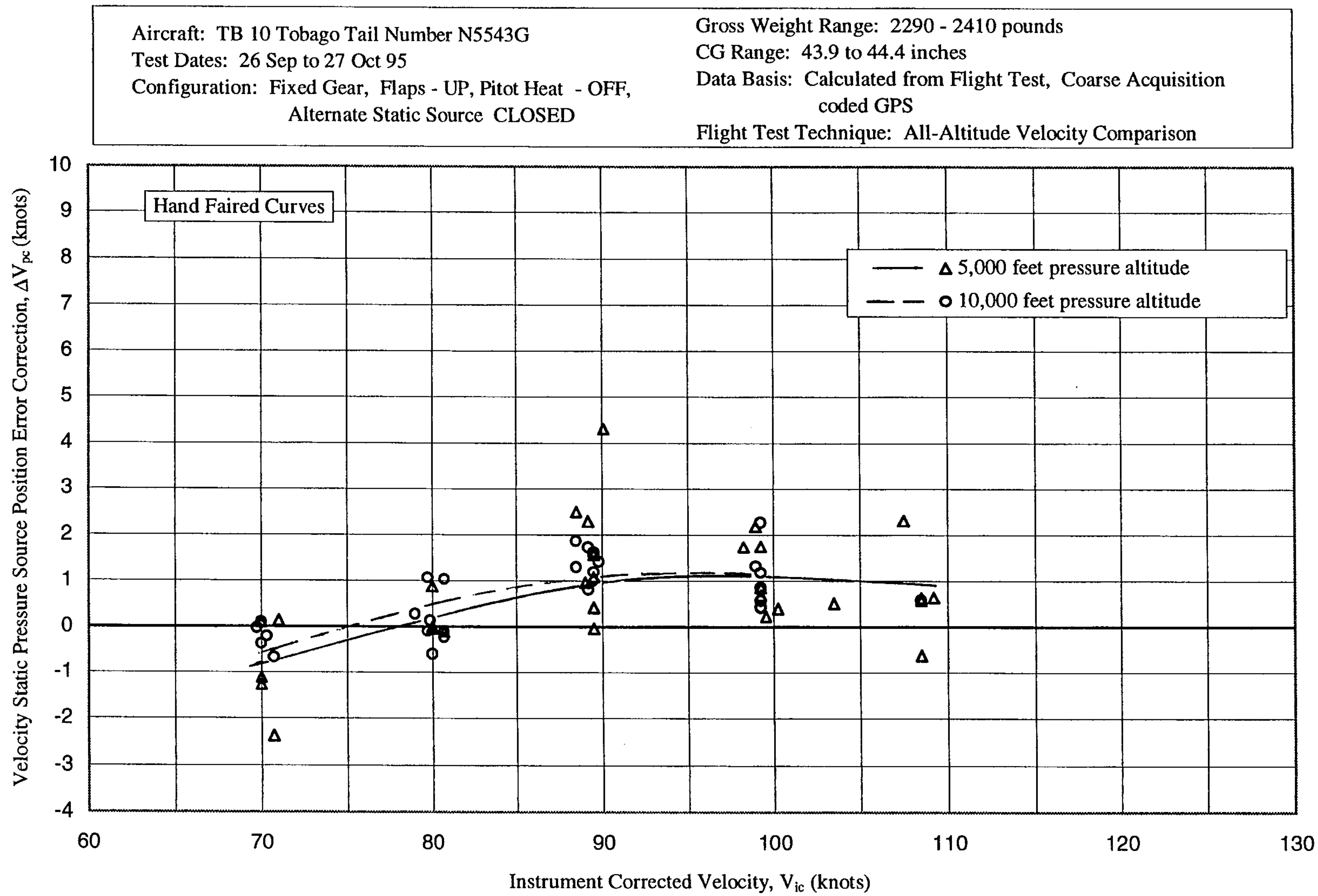

Figure C6 Tobago Velocity Static Pressure Source Position Error Correction

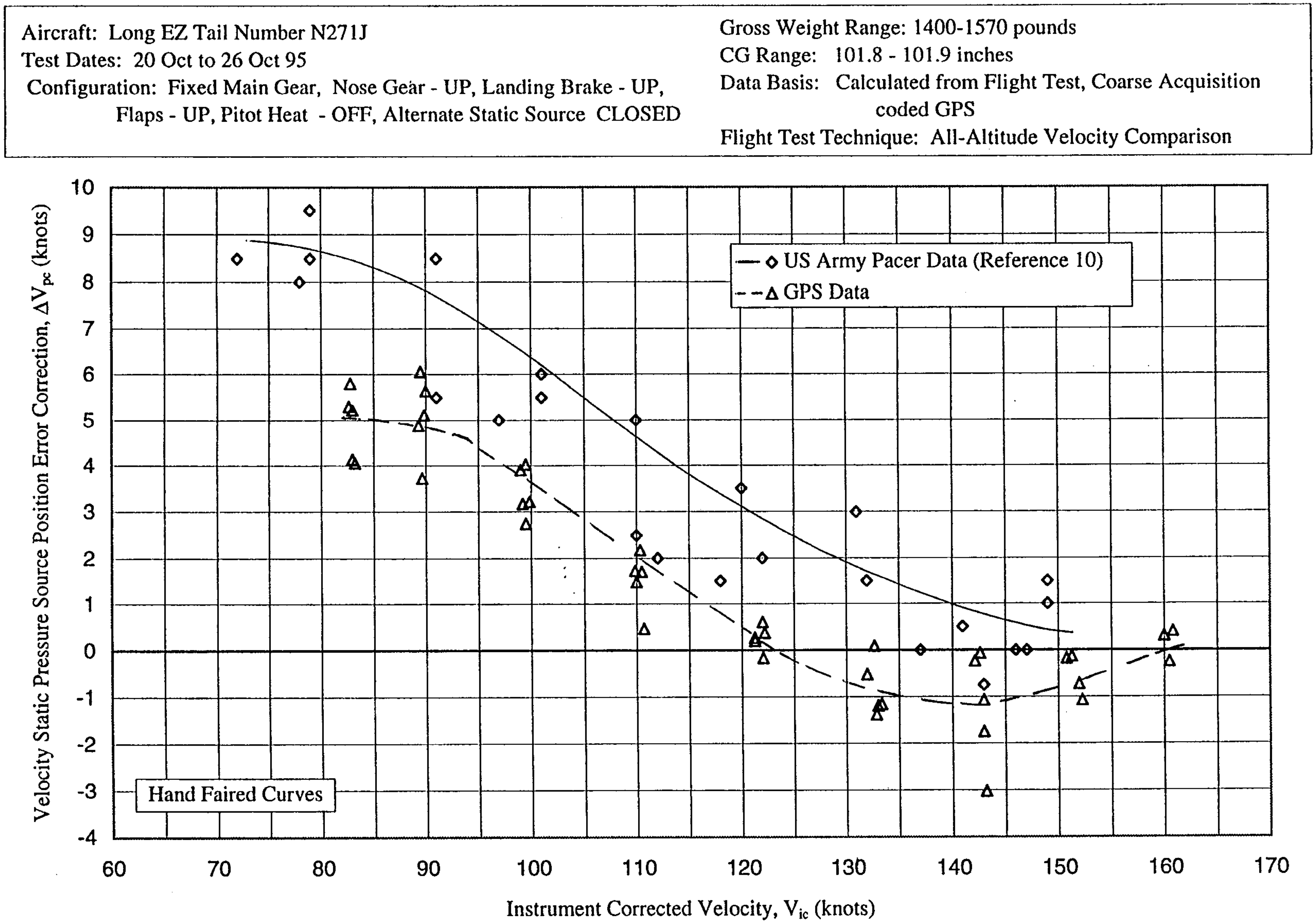

Figure C7 Comparison Between Army Pacer Data and GPS Data on Rutan Long EZ at 4,000 feet Pressure Altitude

Aircraft: Long EZ Tail Number N271J
Test Dates: 20 Oct to 26 Oct 95
Configuration: Fixed Main Gear, Nose Gear - UP, Landing Brake - UP, Flaps - UP, Pitot Heat - OFF, Alternate Static Source

Gross Weight Range: 1400-1570 pounds
CG Range: 101.8 - 101.9 inches
Data Basis: Calculated from Flight Test, Coarse Acquisition coded GPS
Flight Test Technique: All-Altitude Velocity Comparison Method

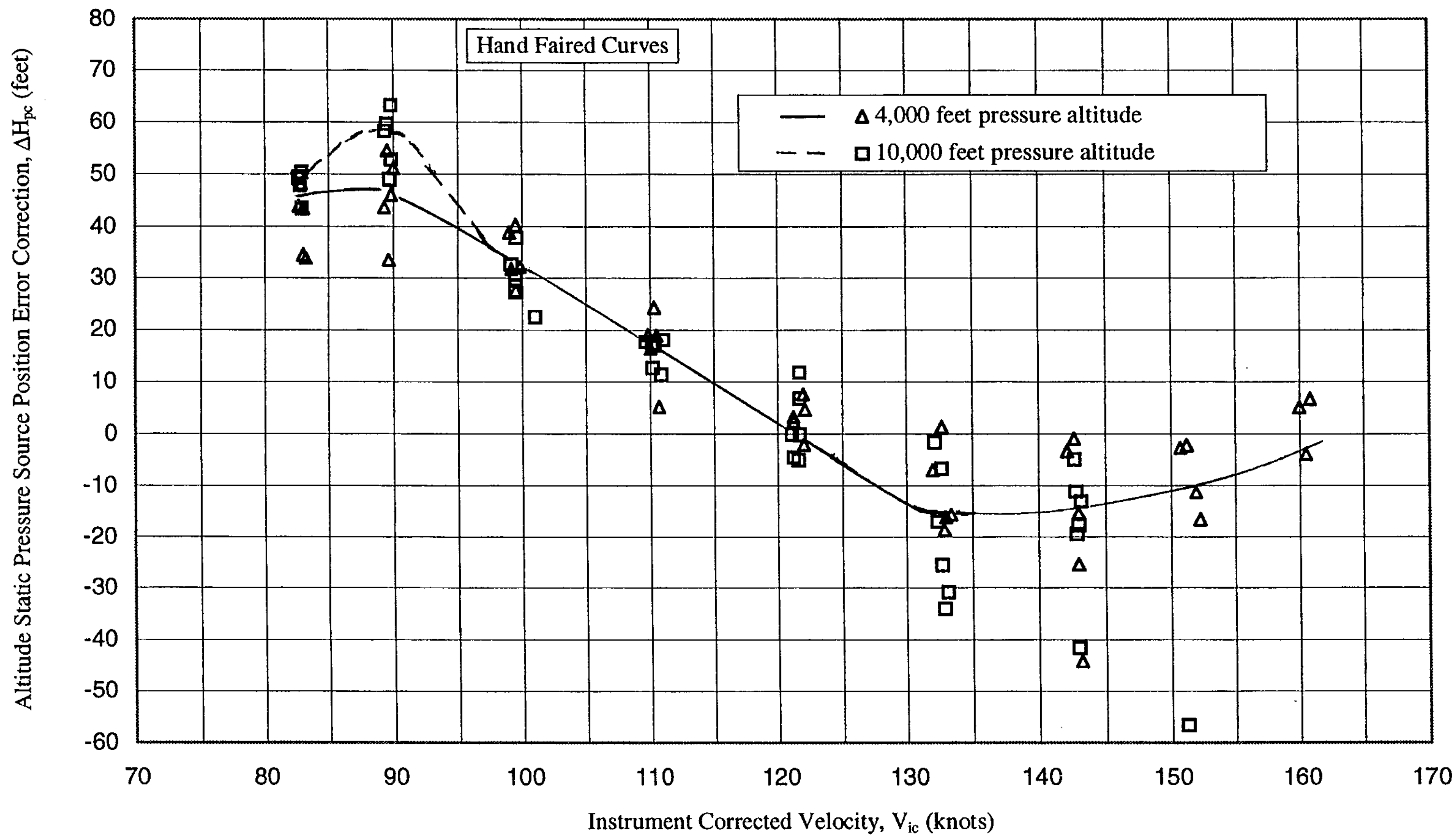

Figure C8 Long EZ Altitude Static Pressure Source Position Error Correction

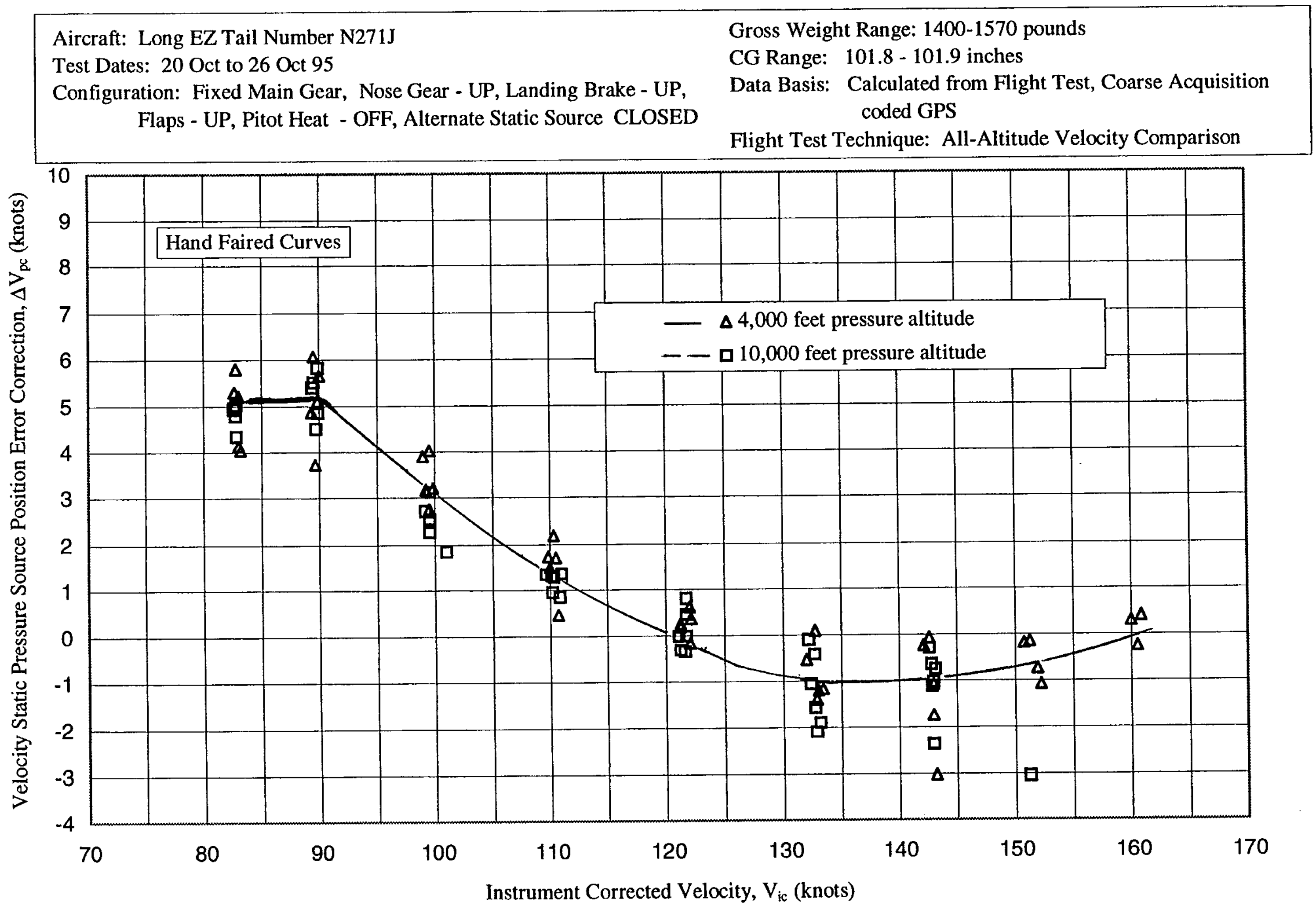

Figure C9 Long EZ Velocity Static Pressure Source Position Error Correction

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APPENDIX D

DATA ANALYSES

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DATA ANALYSIS

STATISTICAL ANALYSIS

A statistical analysis was initiated to achieve the required 90 percent confidence level. This analysis was not rigorous; therefore, several assumptions were made before calculating the bounds. The first assumption made was that the sample taken was homogenous over a range of ±2 knots around the target airspeed. This assumption was based on a sensitivity analysis of the altitude comparison method that showed a 2-knot change had less than a 5 percent effect on the altitude pressure static pressure source position error correction (ΔH_{pc}) or velocity pressure static position error correction (ΔV_{pc}).

To determine the bounds about the means, the data for ΔH_{pc} and ΔV_{pc} were averaged around each airspeed using the range specified above. The sample deviation (s) was then determined for the mean (x). Sample size for all velocities and for all the flight test techniques were usually 5 or 6 points. The student-t distribution was then used to determine a two-tailed confidence interval according to Equation 1.

$$\mu = \bar{x} \pm \left[\frac{t_{\upsilon,1-\alpha/2} \, s}{\sqrt{n}} \right] \quad \text{for } n < 30 \qquad (1)$$

The results of the analysis for both the altitude comparison method tower flyby (TFB) and the groundspeed course are presented in the following tables and plots. Confidence bounds at the 90 percent level were generated for the flyby tower theodolite, the Garmin Global Positionig System (GPS) 100, and the portable lightweight GPS receiver (PLGR+) for the altitude comparison method. For the groundspeed course, confidence bounds were determined for the distance-over-time and Garmin GPS 100 data. For the groundspeed course, no statistically significant difference could be found between the Garmin and PLGR+ groundspeed data. Table D1 summarizes the target, average, and bounds for the TFB data while Table D2 contains the same data for the groundspeed course.

Table D1
ΔH_{pc} CONFIDENCE BOUNDS FOR THE FLYBY TOWER DATA

V_{ic} mean	TFB mean	TFB bound	Garmin mean	Garmin bound	PLGR+ mean	PLGR+ bound
71.30	2.80	2.40	-45.05	84.42	-19.97	16.63
79.57	14.22	1.63	51.49	50.60	-2.77	16.13
90.10	23.50	0.77	99.48	78.79	29.58	14.14
99.10	16.72	0.70	95.24	57.76	9.81	7.33
109.88	9.62	2.15	45.84	15.40	-11.91	19.34
120.12	3.73	2.57	6.08	169.94	-3.34	37.45

Notes: 1. ΔH_{pc} - altitude static pressure source position error correction
2. V_{ic} - instrument corrected velocity
2. TFB - tower flyby
3. PLGR+ - portable lightweight Global Positioning System receiver

Table D2

ΔV_{pc} CONFIDENCE BOUNDS FOR THE GROUNDSPEED COURSE DATA

V_{ic} mean	GSC mean	GSC bound	GPS mean	GPS bound
70.23	-0.58	0.41	-0.33	0.37
79.80	0.36	0.44	0.26	0.36
89.20	0.84	0.39	0.96	0.37
100.00	0.12	0.85	0.40	0.61
109.40	-5.12	0.53	-0.01	0.44
119.13	0.32	0.58	0.57	0.45

Notes: 1. ΔV_{pc} - velocity static pressure source position error correction
2. V_{ic} - instrument corrected velocity
3. GSC - Groundspeed Course

DATA ANALYSIS METHODOLOGY

The data analysis and reduction procedures deserve a closer look since the all-altitude airspeed method is not a classic technique. Figure D1 summarizes the inputs and outputs required in a "big picture" approach. This section will go into greater detail than the test procedures to explain the required data for the flyby tower, groundspeed course, and all-altitude method.

For the TFB method, the aircraft provides velocity, altitude, total temperature and GPS altitude. Instrument correction were then applied, as required. Instruments in the flyby tower provided theodolite data, pressure altitude, temperature, and GPS altitude. The aircraft height above the tower was calculated using the theodolite and with the difference in GPS altitudes. Those two independent measurements were then corrected with the tower ambient temperature to correct to standard day. The standard pitot-static equations were then applied to determine what the measured pressure altitude was from the tower. The two pressure altitudes computed from the theodolite and the GPS altitudes were then compared to the pressure altitude from the aircraft altimeter. The difference was the ΔH_{pc}. Further calculations produced the velocity correction.

The groundspeed course required slightly different data from the aircraft and GPS receiver. Airspeed, pressure altitude, and temperature from the aircraft were corrected for instrument error and entered into the pitot-static equations. Using a stopwatch, distance-over-time measurements were made on the groundspeed course. The GPS receiver provided a similar measurement of Doppler groundspeed. The independent groundspeed measurements were converted to a Mach number and used in the pitot-static equations found in the *Flight Test Engineering Handbook* to determine the ΔV_{pc} (Reference 11). The altitude correction could be found with just a few more calculations.

The all-altitude airspeed comparison method required the same data as the groundspeed course but used a few more equations to massage the GPS data. Again airspeed, pressure altitude, and temperature from the aircraft were corrected for instrument error and entered into the pitot-static equations. In addition to the GPS groundspeed, GPS groundtrack was also required. Assuming that the wind direction was determined according to the procedures described in the body of this report, the direction of travel and the wind direction should be perpendicular. The GPS groundtrack could then be used with the aircraft heading to correct the GPS groundspeed to a true airspeed. Figure D2 depicts the geometry and equation required to correct the GPS groundspeed for drift. Once the true airspeed was found for both directions, the values were averaged and entered into the pitot-static equations. As with the groundspeed course data, the velocity was converted to a Mach number and used to determine the ΔV_{pc}. As before, the altitude correction could be found with just a few more calculations.

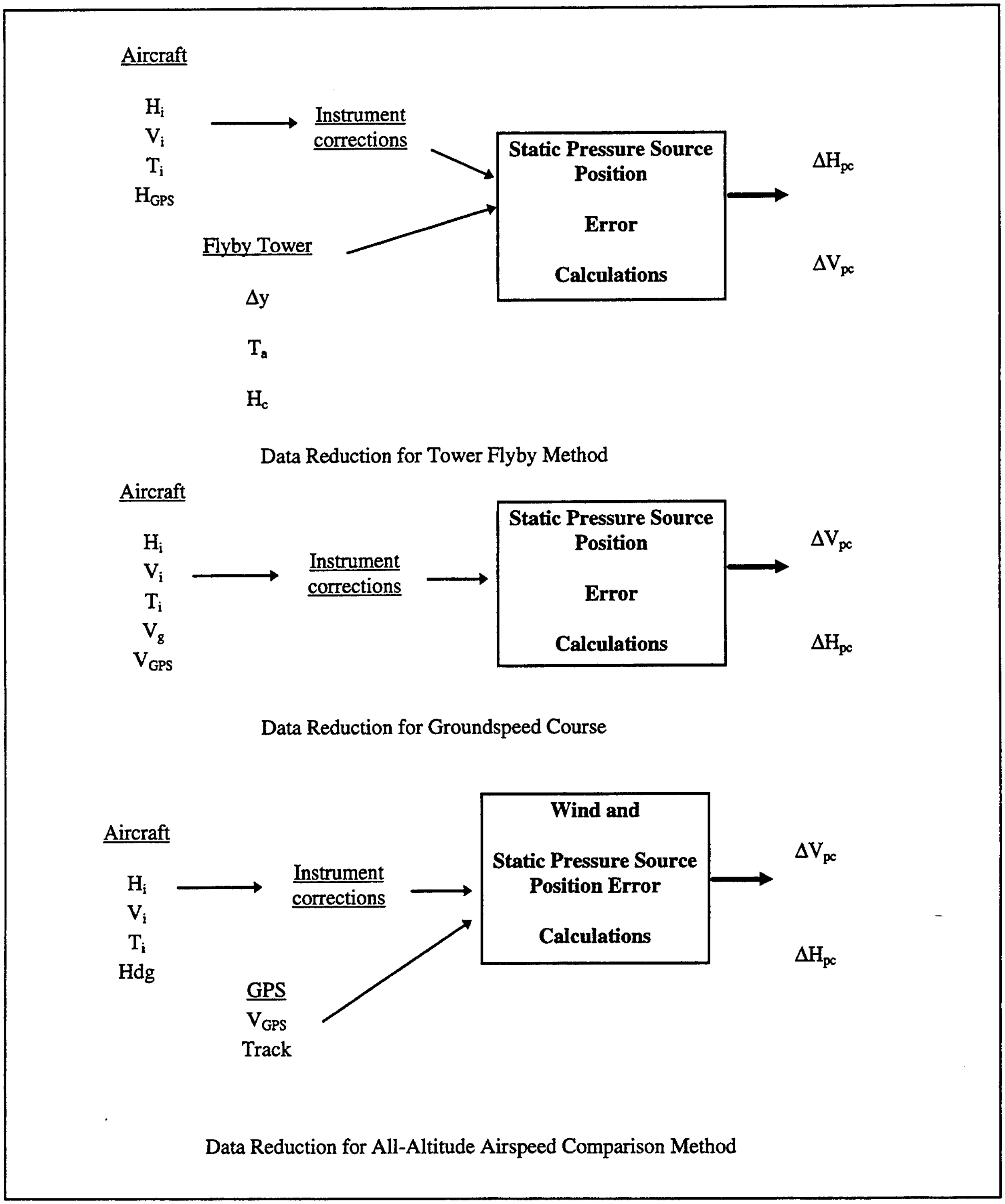
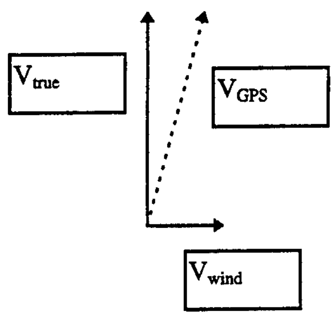


Figure D1 Flowchart for Data Reduction



$$V_{true} = V_{GPS} \cos (\psi - \sigma)$$

where ψ = heading

σ = GPS groundtrack

Figure D2 Correcting GPS Groundspeed for Drift

SENSITIVITY ANALYSIS

A brief analysis was performed on all three methods used in this investigation to determine the sensitivity of the static pressure source position error corrections to various inputs. The first method examined was the TFB. The primary result of this method was the calculation of ΔH_{pc}. Table D3 shows the sensitivity of that parameter to various errors or uncertainties typically found in the input measurements. As expected, the largest impacts come from direct measurements of altitude. A root sum square calculation was made to estimate the uncertainty of this method. The value was on the same order as a more rigorous analysis performed by the Air Force Flight Test Center in 1969 (Reference 12).

In a similar fashion, sensitivities were found for the groundspeed course and all-altitude airspeed comparison method. Table D4 summarizes the sensitivities and an estimated uncertainty for the groundspeed course. Table D5 shows the same for the all-altitude method. No conclusions should be drawn from the sensitivities or the root sum square calculations. The errors or uncertainties in the input parameters are typically worse case values. Therefore, the sensitivities provide a conservative "sanity check" on the estimated accuracies of the methods.

Table D3
ALTITUDE COMPARISON METHOD SENSITIVITIES

Source	Change	Effect on ΔH_{pc} (feet)
Aircraft altimeter at 2,300 feet	10 feet	10.00
Aircraft airspeed at 70 knots	3 knots	0.00
Aircraft temperature	1 degree Fahrenheit	0.00
Theodolite	half a line	15.00
Tower temperature	1 degree Fahrenheit	0.15
Tower pressure altitude	10 feet	10.00
GPS altitude (A/C or tower)	3.28 feet	3.28
Root Sum Square of Changes[1] = 20.6 feet		

Notes: 1. ΔHpc - altitude static pressure source position error correction
2. GPS - Global Positioning System
3. A/C - aircraft

[1]Root Sum Square did not include GPS sensitivity

Table D4
GROUNDSPEED COURSE SENSITIVITIES

Source	Change	Effect on ΔH_{pc} (feet)	Effect on ΔV_{pc} (knots)
Aircraft altimeter at 2,500 feet	10 feet	0.10	0.02
Aircraft airspeed at 70 knots	3 knots	21.15	2.97
Aircraft temperature	1 degree Fahrenheit	0.50	0.07
Timing error	1 second	1.25	0.20
GPS velocity	1 knot	6.50	0.96
ΔWind run to run	5 knots	16.20	2.42
RSS of Changes for Groundspeed Course = 26.95 feet/3.83 knots		RSS for Changes for GPS data = 27.43 feet/3.95 knots	

Notes: 1. ΔHpc - altitude static pressure source position error correction
2. ΔVpc - velocity static pressure source position error correction
3. GPS - Global Positioning System
4. RSS - root sum square

Table D5
ALL-ALTITUDE AIRSPEED COMPARISON METHOD SENSITIVITIES

Source	Change	Effect on ΔH_{pc} (feet)	Effect on ΔV_{pc} (knots)
Aircraft altimeter at 5,000 feet	10 feet	0.15	0.02
Aircraft airspeed at 70 knots	3 knots	18.80	2.95
Aircraft temperature	1 degree Fahrenheit	0.70	0.08
GPS velocity	1 knot	8.30	0.90
Wind velocity variation	5 knots	20.70	2.24
RSS of Changes = 29.2 feet/3.81 knots			

Notes:
1. ΔHpc - altitude static pressure source position error correction
2. ΔVpc - velocity static pressure source position error correction
3. GPS - Global Positioning System
4. RSS - root sum square

APPENDIX E

TEST RUN TABLES

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Table E1

TOWER FLYBY RUN TABLES

Event 1	Maneuver: Tower Flyby Flight Test Technique	Specific Objectives
Priority 1		2.2.1, 2.2.3
Test Limits: 50 feet above ground level minimum, 70 KIAS minimum velocity, Review Threat Hazard Analysis on ground impact		
Data Band: ±5 KIAS, Data Tolerance: Stable (vertical velocity indicator [VVI] = 0, airspeed constant)		
Configuration: Flaps - UP Altimeter set 29.92		
Procedures: 1. Start recording of GPS data on laptop, confirm with flyby tower personnel (ground hog). 2. Perform Tower Flyby Flight Test Technique with target altitude of 100 feet above ground level. 3. Target airspeeds are 100, 110, V_{max}, 90, 80, and 70 KIAS. 4. Record altitude, airspeed, time, temperature, total fuel, and VVI. 5. Ground hog will record theodolite value, temperature, pressure altitude, and time as well as ensure that the GPS receiver in the tower is sending data to the laptop.		

Notes:
1. KIAS - knots indicated airspeed
2. GPS - Global Positioning System
3. V_{max} - maximum speed at maximum thrust

Table E2

GROUNDSPEED COURSE RUN TABLES

Event 2	Maneuver: Groundspeed Course Flight Test Technique	Specific Objectives
Priority 1		2.2.2, 2.2.3
Test Limits: 50 feet above ground level minimum, 70 KIAS min velocity, Review Threat Hazard Analysis on ground impact		
Data Band: ±5 KIAS, Data Tolerance: Stable (vertical velocity indicator [VVI] = 0, airspeed constant)		
Configuration: Flaps - UP Altimeter set 29.92		
Procedures: 1. Start recording of GPS data on laptop, confirm with ground hog. 2. Perform Groundspeed Course Flight Test Technique with target altitude of 100 feet above ground level. 3. Target airspeeds are 100, 110, 115, V_{max}, 90, 80, and 70 KIAS flown both up and down the groundspeed course. 4. Record airspeed, time at distance markers, altitude, temperature, total fuel, and VVI.		

Notes:
1. KIAS - knots indicated airspeed
2. GPS - Global Positioning System
3. V_{max} - maximum speed at maximum thrust

Table E3
ALL-ALTITUDE AIRSPEED COMPARISON RUN TABLES

Event 3	Maneuver: All-altitude Airspeed Comparison Flight Test Technique	Specific Objectives
Priority 1		2.2.3
Test Limits:		
Data Band: ±5 KIAS, ±5 degree Heading ±500 feet Data Tolerance: ±1 KIAS, ±1 degree Heading ±100 feet		
Configuration: Flaps - UP Altimeter set 29.92		
Procedures: 1. Determine a rough idea of the wind direction from weather forecast. 2. Calculate a rough idea of true airspeed based on aim indicated airspeed and outside temperature. 3. Monitor the GPS groundspeed while flying a slow turn through the heading determined to be perpendicular to the wind. 4. When the GPS groundspeed matches the calculated true airspeed, roll out on that heading. 5. Fly the reciprocal of that heading and monitor GPS groundspeed. 6. If the groundspeeds from both directions are within 5 knots, the correct heading has been found. 7. If outside 5 knots, repeat the slow turn until the GPS groundspeeds match. 8. Target airspeeds are 100, 110, 120, V_{max}, 90, 80, and 70 KIAS. 9. Record magnetic heading, airspeed, time, altitude, temperature, GPS groundspeed, and track. 10. Collect data at 5,000 and 10,000 feet pressure altitude.		

Notes: 1. KIAS - knots indicated airspeed
2. GPS - Global Positioning System
3. V_{max} - maximum speed at maximum thrust

LIST OF ABBREVIATIONS, ACRONYMS, AND SYMBOLS

Abbreviation, Acronym, or Symbol	Definition	Unit
A/C	aircraft	---
ADS	air data system	---
AFB	Air Force Base	---
AFFTC	Air Force Flight Test Center	---
AGL	above ground level	---
C/A	coarse acquisition code	---
F	Fahrenheit	degree
FAA	Federal Aviation Administration	---
FAR	Federal Aviation Regulation	---
FTT	Flight Test Technique	---
fps	feet per second	---
GA	general aviation	---
GSC	groundspeed course	---
GPS	Global Positioning System	---
in Hg	inches of mercury	inches
KCAS	knots calibrated airspeed	---
KIAS	knots indicated airspeed	---
LCD	liquid crystal display	---
P	precision code	---
PA	pressure altitude	---
PLGR+	portable lightweight GPS receiver	---
TFB	tower flyby	---
TPS	Test Pilot School	---

LIST OF ABBREVIATIONS, ACRONYMS, AND SYMBOLS (Concluded)

Abbreviation, Acronym, or Symbol	Definition	Unit
USAF	United States Air Force	---
VVI	vertical velocity indicator	---
V_{max}	maximum speed at maximum thrust	knot
V_{ic}	instrument corrected velocity	knot
WAAS	Wide Area Augmentation System	---
Y code	Encrypted Precision GPS code	---
ΔH_{pc}	altitude static pressure source position error correction	knot
ΔV_{pc}	velocity static pressure source position error correction	knot

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